(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
22 May 2003 (22.05.2003)

PCT

(10) International Publication Number
WO 03/043177 A2

(51) International Patent Classification[7]: H03B 28/00, H01S 3/067, G02F 2/00

(21) International Application Number: PCT/US02/36849

(22) International Filing Date: 15 November 2002 (15.11.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/332,372 15 November 2001 (15.11.2001) US
10/116,829 5 April 2002 (05.04.2002) US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:
US 10/116,829 (CIP)
Filed on 5 April 2002 (05.04.2002)

(71) Applicant *(for all designated States except US)*: **HRL LABORATORIES, LLC** [US/US]; 3011 Malibu Canyon Road, Malibu, CA 90265-4799 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **YAP, Daniel** [US/US]; 1824 Sweet Briar Place, Thousand Oaks, CA 91362 (US). **SAYYAH, Keyvan** [US/US]; 1133 24th Street #12, Santa Monica, CA 90403 (US).

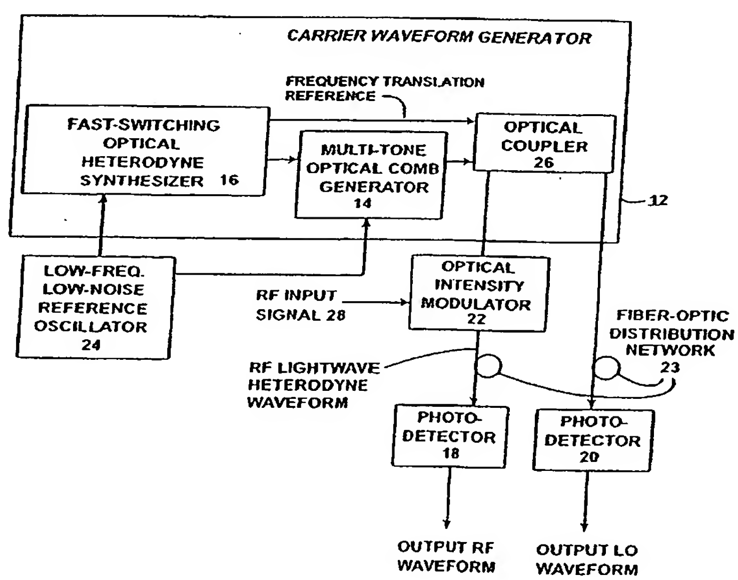
(74) Agents: **BERG, Richard, P.** et al.; Ladas & Parry, 5670 Wilshire Boulevard, Suite 2100, Los Angeles, CA 90036-5679 (US).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK,

[Continued on next page]

(54) Title: AGILE SPREAD WAVEFORM GENERATOR AND PHOTONIC OSCILLATOR



(57) Abstract: An agile spread spectrum waveform generator comprises a photonic oscillator and an optical heterodyne synthesizer. The photonic oscillator comprises a multi-tone optical comb generator for generating a series of RF comb lines on an optical carrier. The optical heterodyne synthesizer includes first and second phase-locked lasers; the first laser feeding the multi-tone optical comb generator and the second laser comprising a rapidly wavelength-tunable single tone laser whose output light provides a frequency translation reference. A photodetector is provided for heterodyning the frequency translation reference with the optical output of the photonic oscillator to generate an agile spread spectrum waveform.

WO 03/043177 A2

TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

Agile Spread Waveform Generator and Photonic Oscillator

Cross Reference to Related Applications

This application is a Continuation-in-Part and claims the benefit of U.S. application number 10/116,829 filed on April 5, 2002, the entire disclosure of which is hereby incorporated herein by reference.

This application claims the benefit of U.S. provisional application number 60/332,372 filed November 15, 2001 for an "Agile Spread Waveform Generator" by Daniel Yap and Keyvan Sayyah, the disclosure of which is hereby incorporated herein by reference.

This application is related to a patent application entitled "Agile RF-Lightwave Waveform Synthesis and an Optical Multi-Tone Amplitude Modulator" bearing serial number 60/332,367 and filed November 15, 2001, and its corresponding non-provisional application bearing serial number 10/116,801and filed on April 5, 2002, the disclosures of which are hereby incorporated herein by this reference. These related applications are owned by the assignee of this present application.

This application is also related to a provisional patent application entitled "Injection-seeding of a Multi-tone Photonic Oscillator" bearing serial number 60/332,371 and filed November 15, 2001, and its corresponding non-provisional application bearing serial number 10/116,799 and filed on April 5, 2002, the disclosures of which are hereby incorporated herein by this reference. These related applications are owned by the assignee of this present application.

This application is also related to a patent application entitled "Remotely Locatable RF Power Amplification System" bearing serial number 60/332,368 and filed November 15, 2001, and its corresponding non-provisional application bearing serial number 10/116,854 and filed on the April 5, 2002, the disclosures of which are hereby incorporated herein by this reference. These related applications are owned by the assignee of this present application.

Technical Field

This disclosure relates to a RF-lightwave waveform generator capable of generating a set of frequency-spread, frequency-hopped RF waveforms. This disclosure further relates to the generation of multi-tone optical combs with a photonic oscillator.

Background

A multi-tone, frequency hopped RF-lightwave waveform functions as a lightwave carrier for an optical transmission channel. The RF signal information carried by the optical transmission channel may be a pulse code, for example, which may be imposed onto the frequency-spread RF-lightwave carrier by means of a lightwave modulator. The final RF-lightwave waveform can be transmitted (by means of an optical fiber link or a free-space optical link) to a photoreceiver. The photoreceived signal, which is in electronic form (frequency converted and demodulated), can then be transmitted through a RF channel (an antenna or wireless link).

As is disclosed herein, the generator of the RF-lightwave carrier includes a frequency-comb generator that is coupled to an optical-heterodyne synthesizer. The comb is a set of RF tones amplitude-modulated onto a lightwave carrier. The generator of the RF-lightwave frequency comb is preferably a photonic oscillator, whose construction is known in the art. The optical heterodyne synthesizer is switchable and produces a pair of phase-locked, CW lightwave lines (at two different optical wavelengths). One of these lightwave lines has the RF comb modulated onto it. Both lines, after being modulated by the comb, are then combined to generate the agile carrier. The center frequency of the photoreceived signal is the heterodyne beat note, which is the difference between the frequencies of the two lightwave lines produced by the optical heterodyne synthesizer. The wavelengths of these lines can be changed rapidly (the wavelengths of these lines can be changed with each transmit pulse, within a single transmit pulse or even within the transmission of a packet of data) to produce different beat-note frequencies. This process hops the center frequency of the resultant multi-tone RF lightwave carrier. Various known methods can be used to realize the optical heterodyne synthesizer.

One purpose of the agile frequency spreading and hopping is to make the resultant signal difficult for a non-coherent receiver to detect. Use of a frequency-spread carrier is one method to produce a signal that has Low Probability of Interception (LPI) by conventional intercept receivers. In addition, if the precise frequency of the carrier can be changed and is unknown to the interceptor, LPI performance is enhanced. These techniques are useful in LPI radar and communication systems.

Typically, an interceptor would use a wideband receiver that is channelized into smaller frequency bands to detect and identify the signal. If the signal falls within a single channel of the receiver, then it can be detected. However, if the signal is spread in frequency so those portions of it fall within many channels, it is difficult for the interceptor to distinguish that signal from the background noise. Typically, the channels of the intercept receiver may be scanned or long integration times may be used to sense an incoming signal. If the signal frequency is varied rapidly to hop between different channels within the sensing time, it again appears like noise. Alternatively, if the signal frequencies are varied rapidly with time although those hops lie within the received channels, that signal will be detected but difficult to identify.

Another purpose of the frequency spreading is to make the signal less susceptible to jamming. The frequency coverage of the jammer may not be as large as the coverage of the frequency-spread carrier. In addition, since the frequency-spread carrier consists of discrete tones that are can be summed coherently, the signal power is used more efficiently. This is in contrast to the jammer, which is uniformly broadband. Rapid switching of the signal band also makes it less susceptible to being jammed, since the jammer cannot predict from one signal pulse to the next which frequency to jam.

Previous methods to achieve LPI performance are based on using electronic synthesizers to produce the waveforms. Typically, a pulse-compression code is used to phase modulate a single-tone carrier and spread the spectrum. For example, if the signal pulse is 1 μsec wide and a 100-to-1 pulse compression code is used, a signal bandwidth of 100 MHz is obtained. The channel bandwidth of the interrogating receiver is typically much narrower than this. The bandwidth of present high-dynamic-range analog-to-digital converters is typically 100 MHz or less. Thus, interrogator channel bandwidths are also 100 MHz or less. This invention

preferably makes use of the wideband nature of photonics to generate the frequency-spread waveforms. The total bandwidth of the comb can be quite wide, with several tens of GHz bandwidths easily achieved by the photonic methods of this invention. A pulse-compression code may be modulated onto the multi-tone comb, in addition to the signal information, to further spread the carrier. Prior art digital synthesizers which produce frequency-stepped waveforms typically have a bandwidth of less than 100 MHz. The switchable, optical-heterodyne synthesizer disclosed herein is capable of a frequency range that exceeds 100 GHz.

The agile frequency spread waveform generator disclosed herein also is useful for communication systems with multiple users. Each user is assigned a particular and unique pattern for the frequency hops of the multi-tone waveform. A user can distinguish its signal from other signals that occupy the same band of frequencies by coherently processing the received signal with a copy of the particular waveform pattern of that user. This type of Code Division Multiple Access (CDMA) for lightwave waveforms is different from prior methods. The prior methods make use of short optical pulses, much shorter than the information pulse, whose wavelength and temporal location can be different for each user.

The prior art includes:

1. A single-tone, single-loop optoelectronic oscillator - see US patent 5,723,856 issued March 3, 1998 and the article by S. Yao and L. Maleki, IEEE J. Quantum Electronics, v.32, n.7, pp.1141-1149, 1996. A photonic oscillator is disclosed (called an optoelectronic oscillator by the authors). This oscillator includes a single laser and a closed loop comprised of a modulator, a length of optical fiber, and photodetector, an RF amplifier and an electronic filter. The closed loop of this oscillator bears some similarity to the present invention. However, the intent of this prior art technique is to generate a single tone by incorporating an electronic narrow-band frequency filter in the loop. A tone that has low phase noise is achieved by using a long length of the aforementioned fiber. Demonstration of multiple tones is reported in this article achieved by enlarging the bandwidth of the filter. However, the frequency spacing of those multiple tones was set by injecting a sinusoidal electrical signal into the modulator. The frequency of the injected signal is equal to the spacing of the tones. This method causes all of the oscillator modes (one tone per mode) to oscillate in phase. As a

result, the output of this prior art oscillator is a series of pulses. See Figure 14 (b) of this article.

2. A single-tone, multiple-loop optoelectronic oscillator - see US patent 5,777,778 issued July 7, 1998 and the article by S. Yao and L. Maleki, IEEE J. Quantum Electronics, v.36, n.1, pp.79-84, 2000. An optoelectronic oscillator is disclosed that uses multiple optical fiber loops, as the time-delay paths. One fiber loop has a long length and serves as a storage medium to increase the Q of the oscillator. The other the fiber loop has a very short length, typically 0.2 to 2 m, and acts to separate the tones enough so that a RF filter can be inserted in the loop to select a single tone. The lengths of the two loops, as well as the pass band of the RF filter, can be changed to tune the frequency of the single tone that is generated. This approach teaches away from the use of multiple optical loops to obtain multiple tones, since it uses the second loop to ensure that only a single tone is produced.

3. 1.8-THz bandwidth, tunable RF-comb generator with optical-wavelength reference - see the article by S. Bennett et al. Photonics Technol. Letters, Vol. 11, No. 5, pp. 551-553, 1999. This article describes multi-tone RF-lightwave comb generation using the concept of successive phase modulation of a laser lightwave carrier in an amplified re-circulating fiber loop. The lightwave carrier is supplied by a single input laser whose optical CW waveform is injected into a closed fiber loop that includes an optical phase modulator driven by an external RF generator. This results in an optical comb that has a frequency spacing determined by the RF frequency applied to the phase modulator and absolute frequencies determined by the wavelength of the input laser. The loop also contains an Er-doped optical fiber amplifier segment that is pumped by a separate pump laser. The effect of the optical amplifier in the re-circulating loop is to enhance the number of comb lines at the output of the comb generator. One may expect some mutual phase locking between the different comb lines since they are defined by the phase modulation imposed by the external RF generator.

4. One technique for generating a RF signal is by optical heterodyning. See Figure 1. With this technique, the optical outputs of two laser wavelengths produced by a RF-lightwave synthesizer are combined onto a photodetector. In one simple case, the RF-lightwave synthesizer consists of two lasers each producing single wavelengths, i.e., single spectral lines. When their combined output is converted by a photodetector into an electronic signal

(the photocurrent), that electronic signal has frequency components at the sum and difference of the two laser lines. Typically, the photodetector also acts as a low-pass frequency filter so that only the heterodyne difference frequency is produced. In order for the heterodyne output to be produced, the two laser lines must be locked together, so that their fluctuations are coherent. Various methods known in the art can be employed to achieve this locking. Optical heterodyning also can be combined with an external optical modulator to perform frequency conversion (frequency translation). This function is illustrated in Figure 1. The dual-line lightwave output of the RF-lightwave synthesizer is supplied to an optical intensity modulator, with a typical modulator being a Mach-Zehnder interferometer. A RF input signal is also supplied to the modulator, which applies an intensity modulation onto the lightwave signal. The transfer function of the modulator results in the generation of frequency sum and difference terms. The output of the photodetector is another RF signal with frequency components that are the sum and difference between the frequencies of the RF input ω_{RF} and the frequency spacing between the two laser lines. In essence, the frequency difference ω_{LO} of the two laser-lines acts as a local-oscillator (LO) frequency that is multiplied with the RF input signal to produce an intermediate frequency (IF) ω_{LO}-ω_{RF}. A mathematical expression for this process is given as:

$$i_D = \frac{\alpha I_o}{2L_{MOD}}\left\{1 + m\sin(\omega_{RF}t) + M\cos(\omega_{LO}t + \phi) \pm \frac{1}{2}mM\sin[(\omega_{LO} \pm \omega_{RF})t + \phi]\right\}$$

where i_D is the photocurrent.

5. A Brillouin opto-electronic oscillator described by Yao in US patent 5,917,179 issued June 29, 1999. The oscillator disclosed by Yao produces a single tone rather than multiple tones. Further, the oscillator makes use of stimulated Brillouin scattering (SBS) in an optical fiber in the opto-electronic feedback path of the oscillator. This feedback path may have one or more optical and/or electrical loops. The SBS produces a second optical signal that also is fed to the photodetector in the path. The frequency of this signal can be different from the frequency of the optical signal output from the optical modulator of the path. The photodetector produces an electrical signal that is the beat of the SBS-produced and the modulator-output optical signals. This beat signal is used to drive the optical modulator and create another modulated output signal that is fed into the optical fiber exhibiting SBS.

Brief Description of the Invention

In one aspect, the present invention provides an agile spread spectrum waveform generator comprising: a photonic oscillator comprising a multi-tone optical comb generator for generating a series of RF comb lines on an optical carrier; an optical heterodyne synthesizer, the optical heterodyne synthesizer including first and second phase-locked lasers, the first laser feeding the multi-tone optical comb generator and the second laser comprising a rapidly wavelength-tunable single tone laser whose output light provides a frequency translation reference; and a photodetector for heterodyning the frequency translation reference with the optical output of the photonic oscillator to generate an agile spread spectrum waveform.

In another aspect, the present invention provides a method of generating an agile spread spectrum waveform, the method comprising the steps of: generating multi-tone optical comb as a series of RF comb lines on an optical carrier; generating a wavelength-tunable single tone frequency translation reference; and optically combining the optical comb with the frequency translation reference to generate a lightwave waveform suitable for subsequent heterodyning.

In still another aspect, an embodiment of the present invention provides a multi-tone photonic oscillator comprising: a first optical branch comprising a first optical delay element; a second optical branch having a main optical fiber, a common path having an optical modulator providing an optical signal to the optical branches, and an electrical portion having least one photodetector coupled to the first optical branch and the second optical branch, the at least one photodetector producing an electrical signal coupled to said optical modulator; and a third optical branch providing a Stokes beam to the second optical branch, the Stokes beam propagating in a reverse direction in the main optical fiber.

In another aspect, an embodiment of the present invention provides a method for generating a multi-tone optical comb, where the method comprises: modulating an optical signal from a laser with an optical modulator to provide a modulated optical signal; delaying the modulated optical signal in a first optical branch to provide a first delayed optical signal; propagating the modulated optical signal in a forward direction in a second optical branch to provide a second delayed optical signal; generating Stokes light from said modulated optical signal; injecting

the Stokes light into the second optical branch so that the Stokes light propagates in a reverse direction to the modulated optical signal in the second optical branch, wherein the Stokes light acts as a seed for stimulated Brillouin scattering in the second optical branch; photodetecting the first delayed optical signal and the second delayed optical signal to produce an electrical signal; and controlling the optical modulator with the electrical signal.

Description of the Drawings

Figure 1 is an illustration of a prior art frequency conversion technique performed with a RF-lightwave synthesizer;

Figure 2 is a block diagram of an agile waveform generator in accordance with the present invention;

Figure 3 is a block diagram of the multi-loop, multi-tone photonic oscillator;

Figure 4 depicts the measured RF spectrum of a multi-loop, multi-tone photonic oscillator;

Figure 5 is a detailed spectrum of one the RF tones of a dual-loop (1 km long loop, 8 m short loop) multi-tone photonic oscillator indicating a very high spectral purity;

Figure 6 is a block diagram of the multi-loop, multi-tone photonic oscillator with optically amplified loops;

Figure 7 is an illustration of fast-switching optical heterodyne synthesizer based on optical injection;

Figure 8 is an illustration of fast-switching heterodyne synthesizer based on a phase locked loop;

Figures 9 is a block diagram of the multi-loop, multi-tone photonic oscillator and a block diagram of the fast-switching optical heterodyned synthesizer consisting of a rapidly

wavelength tunable and a fixed wavelength laser, the photonic oscillator having a fiber length control apparatus and a feedback loop to control the fiber lengths; and

Figure 10 is similar to Figure 9, but instead of having a fiber length control apparatus, it utilizes phase control of the loop to compensate for environment changes in the lengths of the fibers in the multi-loop, multi-tone photonic oscillator.

Figure 11 is a block diagram of an alternative embodiment of a multi-tone photonic oscillator.

Figure 12 shows the spectrum of the optical signal at various points within the oscillator shown in Figure 11.

Figure 13 is a block diagram of another embodiment of a multi-tone photonic oscillator.

Detailed Description

This invention relates to a unique approach in the generation of rapidly frequency hopped or dithered, multi-tone RF comb lines on a lightwave carrier using coherent optical heterodyning in order to make the signal transmitted on these carriers difficult to detect. In the following description of the invention, the concept of optical heterodyning is discussed first, to provide background information. Two embodiments for generating a frequency translatable comb signal are described with reference to Figures 3 - 6. Then, several embodiments for producing a frequency-hopped waveform are described with reference to Figures 7 and 8. Finally, modifications for improved stability are then discussed (with reference to Figures 9 - 11) to one of the two embodiments for generating the frequency translatable comb signal.

The block diagram of an agile waveform generator 12 is shown in Figure 2. It has two main portions 14, 16 that will be described in greater detail with reference to Figures 3 and 6 - 10. The first main portion is a type of photonic oscillator, namely, a multi-tone optical comb generator 14 that generates a series of low-phase-noise RF comb lines on an optical carrier. The second main portion is a fast-switching optical heterodyne synthesizer 16, which

includes two phase-locked lasers 70, 72 (see Figures 7 and 8), the first laser 70 feeding the optical comb generator 14. The second laser 72 is a rapidly wavelength-tunable single tone laser whose output light, a frequency translation reference, is heterodyned with the optical output of the photonic oscillator 14 in a photodetector 18 to generate the frequency hopped RF comb lines (sometimes element 14 herein is referred to as an oscillator and sometimes as a generator - this is due to the fact that "oscillator" 14 "generates" the RF comb). Local oscillator (LO) selector 80 controls the frequency hoping. The agile wavelength offset of the two lasers determines the translation in frequency of the resulting multi-tone RF comb. Furthermore, an optical phase modulator (not shown) can also be inserted in the optical path of the wavelength tunable laser, which can result in further dithering of the multi-tone RF comb in the frequency domain. This effect, combined with the frequency hopping mechanism described above, renders the modulated RF transmit signal very difficult to intercept.

An optical coupler 26 combines the output of the comb generator 14 with the output of the wavelength tunable laser in synthesizer 16. The combined output can be modulated by the RF transmit signal 28 using an optical intensity modulator 22 as shown in Figure 2. In Figure 2 the optical intensity modulator 22 is shown downstream of the optical coupler 26. Alternatively, the optical intensity modulator 22 can be placed between generator 14 and coupler 26 as shown by block 22'. Moreover, the output of coupler 26 can be further modulated by additional pulsed or polyphased codes (or the transmit signal can be modulated by such codes) to reduce the probability of detection (intercept) even more. The pulsed or polyphased codes can be applied at the RF signal input 28 or at a separate optical intensity modulator in series with modulator 22).

A second output of the optical coupler 26 can be used to generate a local-oscillator reference signal from a photodetector 20, which can be conveniently employed in a coherent receiver. An alternate embodiment is to have the RF input signal 26 and any additional codes modulate the output of the comb generator 14 before the modulated output is combined with the frequency translation reference in coupler 26 by moving the optical intensity modulator(s) discussed immediately above upstream of coupler 26 as depicted in Figure 9.

The low frequency low noise reference oscillator 24 provides a timing reference signal to the synthesizer 16 and to the multi-tone oscillator 14.

The modulated frequency hopped RF comb lines available at the output of photodetector 18 are applied to a suitable RF amplifier (not shown) and thence to an antenna (also not shown) for transmission as a communication signal or as a radar pulse, as appropriate to the application in which the present invention is utilized.

Photodetector 18 can be implemented as a portion of the RF amplifier and therefore the RF Lightwave Heterodyne Waveform available from, for example, modulator 22, can be supplied as an optical signal to the RF amplifier. One possible embodiment for an RF amplifier is disclosed in US provisional patent application entitled "Remotely Locatable RF Power Amplification System" bearing serial number 60/332,368 and filed November 15, 2001, and its corresponding non-provisional application bearing serial number 10/116,854 filed on April 5, 2002. The RF Lightwave Heterodyne Waveform could be applied as the sole input to fiber 113 depicted on Figure 2 of that application and then the function of photodetector 18 would be provided by detectors 302 shown on Figure 2 of that application. If the output of photodetector 18 is utilized as an input to the RF amplifier, as disclosed in the US patent application entitled "Remotely Locatable RF Power Amplification System" noted above, then the output of photodetector 18 could be applied as an input to modulator 106 shown on Figure 2 of that application.

The RF-lightwave multi-tone comb generator 14 can be implemented using a variety of techniques. A currently preferred embodiment for this segment of the waveform generator is a multi-loop, multi-tone photonic oscillator 14, a block diagram of which is shown in Figure 3 (an additional block diagram, including additional features, will be discussed later with reference to Figures 6, 9 and 10). The multi-loop, multi-tone photonic oscillator 14 includes at least two loops that preferably have a common portion. An optical modulator 32 is preferably employed in the common portion while lightwave delay paths 34 and 36 and photodetectors 38 and 40 are employed in respective first and second loops. A low-noise electrical amplifier 42 and a RF bandpass filter 44 are preferably also deployed in the loops common portion. The laser light is preferably provided by a laser 70, which supplies the power for the oscillator 14, the laser light being modulated by a RF signal at the electrical input 33 of the modulator 32. The modulated lightwave is then split into two branches, one connected to a shorter optical delay path 34, and the other to a longer optical delay path 36.

The optical signals in the two lightwave paths are sensed by two photodetectors 38 and 40 whose electrical outputs are combined and, following amplification and bandpass filtering, are fed back to the modulator 32, as shown in Figure 3. The bandpass filter 44 sets the bandwidth of the generated RF multi-tone comb spectrum. The two photodetectors 38, 40 can be replaced by a single photodetector (see detector 39 in Figure 10).

The operating principle of this multi-tone oscillator 14 is as follows. Random electrical noise generated in the feedback loops modulates the laser light, which after propagating through the two optical delay paths 34 and 36 and being photodetected is regeneratively fed back to the modulator 32. This positive feedback results in oscillations if the open loop gain is greater than one. If need be, an amplifier 42 may be provided in the loop common portion to add gain. Gain can alternatively be added in the optical loops by using a pump laser (of the type shown, for example, in Figure 6 - see element 29). In the case of a dual-loop photonic oscillator, potential oscillation modes exist at frequency intervals that are an integer multiple of the inverse of the delay times of the two loops (τ_S and τ_L), where τ_S is the delay time of the shorter loop and τ_L is the longer loop's delay time. However, oscillation will only occur at frequencies where the modes resulting from both delay loops overlap, if the sum of the open loop gains of both feedback loops is greater than one and the open loop gains of each feedback loop is less than one. Therefore, oscillation will only occur at modes spaced at the frequency interval determined by the shorter loop ($\Delta f = k/\tau_S$). On the other hand, the oscillator phase noise $S(f')$ decreases quadratically with the optical delay time in the longer loop: $S(f') = \rho/[(2\pi)^2(\tau_L f')^2]$, where ρ is the input noise-to-signal ratio and f' is the offset frequency. Combining these two effects results in a multi-tone, multi-loop photonic oscillator in which the tone spacing and phase noise can be independently controlled.

The measured RF spectrum of a dual-loop, multi-tone photonic oscillator spanning a frequency range of 1 GHz is shown in Figure 4. This oscillator has two fiber optic delay loops, with a shorter loop of about 8 m (or longer) and a longer loop of about 1 km (or longer). When the length of the shorter loop is 8 m, the tone spacing is about 26 MHz, indicating a delay time of 38 nanoseconds. The detailed RF spectrum of one of the oscillation tones in the dual-loop multi-tone photonic oscillator is shown in Figure 5, indicating an

excellent spectral purity. The frequency span is 5 KHz. The length of the longer loop is preferably at least 40 or more times longer than the length of the shorter loop.

In another embodiment, the multi-tone photonic oscillator 14 can be implemented using optical amplifiers, as shown in Figure 6, instead of electronic amplifiers, as previously discussed with reference to Figure 3. In this embodiment, each loop preferably includes an isolator 25, an Er-doped or an Yb/Er-doped fiber segment 27, and a wavelength division multiplexer (WDM) 31. Each doped fiber segment 27 is preferably pumped by a pump laser 29, although the pump laser 29 and the associated Er-doped or Yb/Er-doped segment 27 could be employed in only one of the loops, if desired. The isolators 25 keep the light flowing in the correct direction (clockwise in Figure 6) in the loops and also keep the light from the pump laser 29 from interfering with the operation of the modulator 32. The WDMs 31 couple the light from the pump laser 29 into the loops and keep that light from interfering with the function of the photodetectors 38, 40. The two photodetectors 38, 40 may be replaced with a single photodetector 39 as shown in Figure 10 if desired, and two pump lasers 29 could be used (one for each loop), if desired.

Several techniques can be used to realize the fast-switching optical heterodyne synthesizer 16. See Figures 7 and 8 for exemplary embodiments. In the embodiments of Figure 7 and 8, the synthesizer 16 includes the two previously mentioned lasers 70 and 72. These lasers are phase-locked. The first laser 70 is a fixed wavelength laser and the second laser 72 is a rapidly tunable laser. This phase locking can be accomplished using several known techniques. One of these techniques, and the preferred technique, is illustrated in Figure 7. This technique involves optical injection locking of the two lasers 70 and 72 (the slave lasers) to different lines of a multiline master laser 76. These lines can be: (1) different modes of a mode-locked master laser, (2) modulation sidebands of a frequency modulated master laser, or (3) different phase-locked modes of a multiline laser (see the comb generator disclosed by prior art references 1 and 3).

A highly stable and low phase-noise, single tone RF reference oscillator 78 may be used to externally lock the mode locked laser 76 (if using alternative 1 mentioned above), frequency modulate the master laser 76 (if using alternative 2 mentioned above), or phase modulate the

multiline laser 76 (if using alternative 3 mentioned above). The RF reference oscillator 78 may be further stabilized or synchronized by an additional reference oscillator 24 as discussed with reference to Figure 2.

The optical output of the multi-tone comb generator 14, which is fed by the fixed wavelength laser 70, is an optical comb containing the laser wavelength modulated by the RF comb lines Combining this optical comb with the rapidly tunable wavelength of the second laser 72 in photodetectors 18 or 20 results in a set of RF comb lines which can be rapidly switched (hopped) in the frequency domain. The frequency-hopping interval is determined by the wavelength interval over which the second laser 72 is stepped. With the optical injection locking approaches described above (see the embodiment of Figure 7), this interval is determined by the spacing between adjacent modes or sidebands of the multiline master laser 76. If the mode spacing for the multiline master laser 76 is 5 GHz, and the bandwidth of the comb is 5 GHz, the center frequency of the comb can be hopped rapidly between 5 GHz and 10 GHz and 15 GHz, and so on, in any order. Since these two lasers 70 and 72 are phase-locked, as described above, the resulting frequency-switchable heterodyned RF tones will have good spectral purity and low phase noise. Note should be made of the fact that the frequency-hopping interval can be smaller than the bandwidth of the comb.

Another technique for phase locking laser 70 and 72 involves a phased locked loop (see Figure 8).

The phase-lock loop embodiment of Figure 8 takes the heterodyned output of the two lasers 70 and 72 and compares that output with an external RF reference 82 in a RF phase detector to produce an error signal 90 at the output of a mixer 86 for correcting the wavelengths of the lasers 70, 72. The outputs of the two lasers 70, 72 are coupled by coupler 85 and detected by photodetector 87 where the heterodyned electrical signal is produced. The output of detector 87 is preferably frequency-divided down by a frequency divider 84 and the output of the frequency divider 84 is applied to the mixer 86. With this approach, the wavelength difference between the two phase-locked lasers 70, 72 can be varied in steps equal to the steps of the frequency divider 84. If continuous tuning is desired then the RF reference 82 should be continuously tunable. A variation of the phase-locked loop approach involves using wavelength intervals that are larger than the frequency of the RF reference. The frequency

divider 84 divides the heterodyne output of the two lasers to a lower frequency that can be compared with the RF reference 82 by mixer 86, as illustrated in Figure 8. The frequency-hopping interval would then be equal to the divider ratio multiplied by the minimum step of the tunable RF reference 82. The embodiment of Figure 8 permits the hopping to be very fine, so fine that the signal seems essentially continuous. The output 27 of the coupler 85 has hopping information useful to an associated receiver when used in a radar application, for example.

These four alternatives (the three alternative discussed with reference to Figure 7 and the alternative of Figure 8) have different advantages and disadvantages. Generally speaking, alternative (1) (which is associated with Figure 7) generates very clean tones that are easy to switch between. Alternative (2) yields fewer tones. Alternative (3) yields a large number of tones, but they are not clean. Alternative (4) requires lasers that have either a very narrow linewidth or a phase locked loop with a very short loop delay time.

The LO selector 80 shown in Figure 7 adjusts the free-running frequency or wavelength of laser 72 to match the desired line output from multiline master laser 76. This is accomplished by setting the temperature and drive current of laser 72. The LO selector 80' shown in Figure 8 sets the temperature of laser 72 to obtain a desired free-running frequency or wavelength for that laser. The actual laser frequency or wavelength is fine tuned by controlling its drive current by means of the phase lock loop. LO selector 80' also selects the frequency of the tunable oscillator 82 as well as the divide ratio of the frequency divider 84.

Figure 9 is a block diagram of the multi-loop, multi-tone photonic oscillator 14, the photonic oscillator having a fiber length control apparatus 92 and a feedback loop to control the fiber lengths of delay lines 34 and 36. The delay lines 34 and 36 are apt to be sufficiently long that as they change length in response to changes in temperature of their environment, the change in temperature will adversely affect the phase of the oscillator 14. Thus, some means for compensating or controlling the tendency of the fibers 34 and 36 to change length in response to changes of environmental temperature is desirable. In Figure 9 fiber length control apparatus 92 may be a heating and/or cooling apparatus for heating and/or cooling at least the fibers 34 and 36 in order to control their lengths or fiber length control apparatus 92 may physically stretch the fibers 34 and 36 in order to control their lengths. For example, fiber

length control apparatus 92 can comprise piezoelectric fiber stretchers that adjust the fiber lengths. A feedback circuit preferably comprising a frequency divider 94, a tone select filter 96, a mixer 98 and a filter 100 is utilized to control apparatus 92. The frequency divider divides down the output of modulator 32' and tone select filter 96 selects one of the generated and frequency reduced tones for comparison against a reference tone available from, for example, reference oscillator 24 by mixer 98. The output of mixer 98 is filtered to remove unwanted mixing products and then applied as a control signal to fiber length control apparatus 92. In that way, the lengths of the fibers 34 and 36 are adjusted in response to changes in one of the frequencies generated by the photonic oscillator 14.

The optical intensity modulator of the embodiment shown in Figure 9 is preferably implemented as an electroabsorption modulator 32'. An electroabsorption modulator 32' not only modulates the amplitude of the lightwave carrier supplied by laser 70 but it also produces a photocurrent 93 that is fed to the frequency divider 94 in the feedback circuit. Alternatively, the feedback from the loops may be obtained at the outputs of the photodetectors 38, 40. Also, the two photodetectors 38, 40 may be replaced by a single photodetector 39 as shown in Figure 10.

Figure 10 is similar to Figure 9, but instead of having a fiber length control apparatus 92, it utilizes phase control of the loop to compensate for environmental changes in the lengths of the fibers 34, 36 in the multi-loop, multi-tone photonic oscillator 14. An optical phase shifter 91 is placed in the multi loops of the multi-tone comb generator 14 and is utilized in lieu of the fiber length control apparatus 92 to compensate for changes in the lengths of fibers 34 and 36. The feedback circuit of Figure 9 is used to control the optical phase shifter 91. This feedback circuit taps off a portion of the photodetected and amplified multi-tone waveform to determine its departure from the frequency and phase of the reference oscillator 24.

Only one photodetector 39 is depicted receiving the light from loops 34 and 36 in Figure 10. This is only an apparent simplification. One photodetector 39 might seem simpler than two photodetectors 38, 40, but the use of one photodetector 39 will usually require tight phase control between the two loops so that an out-of-phase condition between the two loops does not cause the light to sum incorrectly (or even cancel). Thus, the use of two photodetectors 38

and 40, one associated with each delay line 34 and 36, is preferred for all embodiments, including the embodiment of Figure 10.

The multi-tone, optical comb generator 14 can alternatively be of a prior art design, such as that disclosed by reference 1 or even possibly reference 3 mentioned above. Such a design is not preferred because of its non-continuous output.

Injection seeding of the photonic oscillator 14 may be needed to initiate oscillations in multiple tones. A suitable injection seeding scheme is disclosed in the US patent application entitled "Injection-seeding of a Multi-tone Photonic Oscillator" referred to above.

In another embodiment of the present invention, the multi-tone photonic oscillator 14 can be implemented using an additional loop in its optical feedback path, as shown in Figure 11. The additional loop produces a Stokes seed for stimulated Brillouin scattering (SBS) in the long loop of the multi-tone photonic oscillator 14. The use of SBS in the optical fiber loop of the photonic oscillator 14 attenuates those tones produces by the oscillator 14 whose intensities exceed some threshold value, as described in additional detail below. Having the intensities of the tones clamped at a threshold value produces a multi-tone waveform whose tones are more uniform in intensity. More uniform tone intensities may produce a RF carrier waveform that is more desirable for use in RF sensor systems, such as those in which low probability of interception is a design goal.

Similar to the multi-tone photonic oscillator 14 depicted in Figure 3, the multi-tone photonic oscillator 14 shown in Figure 11comprises an optoelectronic feedback loop that has a RF-lightwave output. A laser 70 supplies an optical signal with an optical carrier to the oscillator 14. An optical modulator 32 modulates the light from the laser 70, resulting in a RF-lightwave output whose frequency spectrum consists of the optical carrier and modulation sidebands. Generally two sets of sidebands are produced, which are at frequencies higher and lower than the optical carrier, respectively. For a multi-tone oscillator, the modulation sidebands comprise multiple frequency tones. The photonic oscillator 14 may be used in combination with a photodetector (not shown in Figure 11) that is connected to the output of the photonic oscillator 14. That photodetector converts the RF-lightwave signal into a RF signal whose frequency spectrum likewise has multiple tones.

The optoelectronic feedback loop of the multi-tone photonic oscillator 14 contains two optical branches or paths and a common electrical and optical path. The common path contains at least the modulator 32, an optical coupler (VOC) 195 or splitter, an electrical combiner (2:1) 197 and an electrical bandpass filter (BPF) 44. The common path may also contain one or more electronic amplifiers (AMP) 42 and optical amplifiers (OA) 201 as well as electrical or optical variable phase shifters ($\Delta\Phi$) 191. The optical coupler 195 could be variable so that the relative amounts of power in its multiple outputs are varied. Those skilled in the art will understand that the relative locations of some of these components may be changed or that some of the components may be eliminated in accordance with alternative embodiments of the present invention.

A first optical branch or path contains at least a photodetector (PD) 38 and an optical delay element 234. This delay element 234 could be a length of optical waveguide or fiber. The overall time delay of the signal that traverses the first optical branch and the common path establishes the frequency spacing of the multiple tones produced by the photonic oscillator 14. A fiber length of 2 meters would result in a tone spacing that is on the order of 100 MHz, for example. For the photonic oscillator 14 according to embodiments of the present invention, that frequency spacing is preferably larger than the gain bandwidth of Stimulated Brillouin Scattering (SBS). That gain bandwidth is typically 30-50 MHz or smaller, for high-quality optical fiber.

A second optical path contains another photodetector 40 and optical components that produce a longer delay than the first path. These optical components may simply comprise a long length of optical fiber (> 100 meters). However, in the multi-tone photonic oscillator 14 depicted in Figure 11, the second path makes use of the SBS effect, as described in additional detail below.

As indicated, the multi-tone photonic oscillator 14 shown in Figure 11 makes beneficial use of Stimulated Brillouin Scattering (SBS), which typically is an undesired non-linear effect that occurs in optical fiber. SBS is a well-known effect that can be observed especially in long lengths of uniform optical fiber or in high-Q optical-fiber resonators and at high optical power levels. SBS is described in some detail in the book Nonlinear Fiber Optics by G. P.

Agrawal (Academic Press, 1995). When SBS occurs, some of the energy in the light propagating in the forward direction is coupled into light propagating in the reverse direction. This phenomenon is a non-linear effect in the optical fiber that is related to certain vibrational-excitation modes (acoustic phonons) of silica (the constituent material in optical fiber). Essentially, a photon of the forward-propagating light (at frequency ν_P) is annihilated to create a photon of the reverse-propagating light (at a down-shifted Stokes frequency ν_S) as well as an acoustic phonon of the proper energy and momentum. The amount of down shift is usually called the Stokes shift and can be described by $\nu_B = 2v_s/(c/n)\ \nu_P$. ν_B is approximately 11 GHz for light of 1.5-mm wavelength, where v_s and (c/n) are the speeds of the sound and light in the fiber, and ν_P is the optical frequency of the forward-propagating light. The SBS effect has a finite bandwidth that is typically described as the Brillouin gain bandwidth. This bandwidth $\Delta\nu_B$ is about 30-50 MHz for silica fibers at 1.5mm, but it can be broader if there are inhomogeneities in the fiber due to manufacturing, temperature or stress variations along the fiber. If the forward-propagating light comprises multiple tones that have a frequency spacing greater than the bandwidth $\Delta\nu_B$, each tone interacts independently with the silica medium.

For small signals, the growth of the reverse-propagating Stokes light can be described by an exponential relation, $\exp[g(\nu)\,(P_p/A_c)L_{eff}]$. Here $g(\nu)$ is the gain coefficient, P_p is the forward-propagating "pump" power, A_c is the effective core area of the fiber and L_{eff} is the effective fiber length (that is, $[1- \exp(-\alpha L)]/\alpha$, where L is the fiber length and α is the absorption coefficient). $g(\nu)$ has a Lorentzian line shape with a peak at $\nu_S = \nu_P - \nu_B$, and bandwidth $\Delta\nu_B$. $g(\nu_S)$ has a value of about 5×10^{-11} cm/W for pure silica fibers and it is wavelength independent. SBS is a stimulated-conversion process that can be described as having a threshold. For conditions, such as optical power levels above the threshold, that process is appreciable. For conditions below the threshold, that process is minor. SBS thresholds at 1550 nm wavelength have been measured for several common types of optical fiber (see, for example, C.C. Lee and S. Chi, IEEE Photonics Technology Letters, 2000, vol. 12, no. 6, p. 672). For example, thresholds are typically between 5-10 mW for 25 km lengths of fiber. Note that this would be the threshold for each tone separated in frequency by more than the SBS bandwidth. For input powers higher than the SBS threshold pump power P_{thres}, the transmitted power is clamped to approximately $(P_{thres})\exp(-\alpha L)$ and the excess power (P_p

- P_{thres}) is converted into a strong Stokes beam propagating in the backward direction. The effective bandwidth of the interaction also is reduced, to $\Delta\nu_B/(g_0 L_{eff})^{1/2}$, due to exponential gain in the stimulated scattering process. SBS can be significant in the long branch of the photonic oscillator 14 if that branch contains a sufficiently long length of optical fiber and high levels of optical power in the multiple tones.

The effect of SBS in the photonic oscillator depicted in Figure 11 is illustrated in Figure 12 which shows both sets of modulation sidebands in the RF-lightwave signal. The spectrum of light input to that fiber is illustrated at line a of Figure 12. This spectrum also corresponds to the spectrum that would be seen at point "a" of Figure 11 at the output of optical amplifier 201 immediately following the optical coupler 195. The forward-propagating light output from the fiber has a spectrum that is illustrated at line c of Figure 12. This spectrum also corresponds to the spectrum that would be seen at point "c" of Figure 11 at the output of the circulator 211. Note that the power in each tone has been clamped to some threshold value. That power is converted into the backward-propagating light, whose spectrum is illustrated in a line b of Figure 12.

It would generally be difficult to achieve the high levels of optical power, per tone, that is needed for the SBS clamping effect to be significant. The additional elements of the multi-tone photonic oscillator 14 provide a means to accomplish that SBS clamping at lower levels of optical power in the incident, forward-propagating light. The photonic oscillator 14 illustrated in Figure 11 contains an additional optical branch or loop. This loop contains two optical circulators (CIR) 211, a length of optical fiber 251 and one or more optical amplifiers 201. The loop may also contain variable optical attenuators 213. The Stokes light from the second optical branch is directed into the additional optical loop by means of the two circulators 211. This Stokes light is amplified before being reinjected, in the reverse direction, into the second optical branch. The Stokes light injected from the loop acts as a seed for SBS in the optical fiber 251 of the second optical branch. The seeding is effective because SBS depends on the intensities of both the reverse-propagating Stokes light and the forward-propagating light. The gain obtained from each optical amplifier in the additional loop can be greater than 20 dB. Thus, the SBS power threshold of the incident, forward-propagating light could be reduced substantially.

As briefly discussed above, the spectra that could be observed at points "a," "b" and "c" of the photonic oscillator shown in Figure 11 are illustrated in Figure 12. Note that the spectrum of the signal exiting the second branch (as shown a line c of Figure 12) has tones of more uniform intensity than the spectrum of the signal entering the second branch (as shown at line b of Figure 12). Also, the power at the optical carrier frequency 295 is reduced.

In another embodiment of the present invention, the multi-tone photonic oscillator 14 can be implemented using a different configuration of a loop in its optical feedback path, as shown in Figure 13. The photonic oscillator 14 shown in Figure 13 has a different implementation of the loop that provides the Stokes light that seeds the SBS in the second optical path. With this approach, a fraction of the input signal (typically, 0.1 - 1 mW) is fed into a recirculating ring. This ring contains a loop of optical fiber 261, an optical circulator 211 and 2 X 2 coupler 223 for coupling light into and out of the ring. The ring recirculates both the input light tapped, at frequencies ν_P, and the Stokes shifted light, at frequencies ν_S, produced by SBS in the ring. The threshold pump power for SBS oscillations is reduced in a ring because of the recirculation. That threshold is set so that all or almost all tones produce appreciable Stokes shifted energy. A portion of the Stokes shifted light from the ring is tapped off and is fed into the far end of the main SBS fiber (which is in the second optical branch) such that it counterpropagates to the signal-carrying light. In the main SBS fiber, the Brillouin amplification of this Stokes-shifted light at ν_S clamps the intensities of the various incident tones at ν_P. As with the photonic oscillator illustrated in Figure 11, a Stokes seed is being provided for the SBS effect.

The second optical branch in the photonic oscillator 14 shown in Figure 13 contains an optical isolator (ISO) 217, an optical splitter (1 X 2) 221, a length of optical fiber (the main SBS fiber) 251 and an optical circulator 211. This branch also could contain a second optical circulator 211 that provides an output port for monitoring the Stokes light in the branch. The isolator 217 and the circulators 211 keep the Stokes light and Stokes-shifted frequency components from feeding into the common path of the photonic oscillator 14. A portion of the light output from the optical splitter 221 is coupled into the main SBS fiber 251. Another portion is coupled into the ring. The optical circulator 211 associated with the ring separates the signal light to be coupled into the ring from the Stokes light coupled out of the ring. The 2 X 2 coupler 223 couples a portion of the signal light into the ring and a portion of the

Stokes light (produced by SBS in the ring) out of the ring. The minimum length of the ring and the coupling strength of the 2 X 2 coupler 223 are selected to ensure that a Stokes seed of sufficient power is generated. The ring also could contain additional optical amplifiers 201 that result in amplification of the Stokes seed.

The recirculating ring shown in Figure 13 is an optical resonator that can be described by a set of resonance frequencies, each having a linewidth. Since the tones of the RF-lightwave signal produced by the photonic oscillator 14 are known, the ring can be designed to have a subset of those resonance frequencies coincide with the optical frequencies of the tones. This adjustment of the resonance frequencies can be done by adjusting the length of the fiber 261 in the ring. It would be preferable to design the ring resonator to have a linewidth that is larger than anticipated drift in the tone frequencies. Common SBS ring resonators have a finesse of 100 or larger. The coupling strength of the 2 X 2 coupler 223 determines the linewidth of the ring resonator, since the attenuation of light in the fiber ring is so small. The optical spectra illustrated in Figure 12 also could be observed at the points labeled "a," "b" and "c" in Figure 13. Again, the intensities of the tones exiting the second branch are clamped. Some adjustment of the gains of the electronic amplifiers 42 and optical amplifiers 201 as well as the attenuations of the various variable optical attenuators 213 may be needed to achieve the desired threshold levels for ensuring uniform tone intensities. The coupling strength of the 2 X 2 coupler 223 and the length of the fiber 261 in the ring may also be adjusted to obtain the desired tone intensities.

Note that the frequencies of the Stokes light are typically offset by > 10 GHz from the frequencies of the tones produced by the multi-tone photonic oscillator. Since the frequency range covered by those tones is generally less than 5 GHz, it is possible to select the frequency band of those tones such that the optical frequencies of the Stokes light and the photonic-oscillator tones do not overlap, for both the upper and lower modulation sidebands. For example, centering the multiple tones about 15 GHz would accomplish this objective. In this way, the bandpass filter 44 of the common path could further attenuate any spurious tones that may result from the SBS.

As briefly discussed above, the tone spacings for the multi-tone photonic oscillators 14 illustrated in Figure 11 and 13 are preferably greater than the SBS bandwidth. That is, the

SBS bandwidth is typically greater than 50 MHz. Therefore, the tone spacings for the oscillators in Figures 11 and 13 are preferably greater than 50 MHz.

Having described the invention in connection with a preferred embodiment therefore, modification will now certainly suggest itself to those skilled in the art. As such, the invention is not to be limited to the disclosed embodiments except as required by the appended claims.

What is claimed is:

1. An agile spread spectrum waveform generator comprising:
(a) a photonic oscillator comprising a multi-tone optical comb generator for generating a series of RF comb lines on an optical carrier;
(b) an optical heterodyne synthesizer, the optical heterodyne synthesizer including first and second phase-locked lasers, the first laser feeding the multi-tone optical comb generator and the second laser comprising a wavelength-tunable single tone laser whose output light provides a frequency translation reference; and
(c) a photodetector for heterodyning the frequency translation reference with the series of RF comb lines on the optical carrier generated by the photonic oscillator to generate an agile spread spectrum waveform.

2. The apparatus of claim 1, wherein the apparatus comprises an agile spread spectrum waveform generator.

3. A multi-tone photonic oscillator comprising:
a laser producing an optical carrier wave;
a first optical branch comprising a first optical delay element;
a second optical branch comprising a main optical fiber having a forward direction of light propagation;
a common path, said common path comprising:
an optical portion having an optical modulator receiving said optical carrier wave and providing an optical signal to said first optical branch and said second optical branch, and
an electrical portion having at least one photodetector coupled to said first optical branch and said second optical branch, said at least one photodetector producing an electrical signal coupled to said optical modulator; and
a third optical branch, said third optical branch providing a Stokes beam to said second optical branch, said Stokes beam propagating in said main optical fiber in a direction opposite to said forward direction of light propagation.

4. The apparatus of claim 3, wherein the apparatus comprises a multi-tone photonic oscillator

5. A method of generating an agile spread spectrum waveform, the method comprising the steps of:

(a) generating a multi-tone optical comb as a series of RF comb lines on an optical carrier;

(b) generating a wavelength-tunable single tone frequency translation reference; and

(c) optically combining the optical comb with the frequency translation reference to generate a lightwave waveform suitable for subsequent heterodyning.

6. A method of generating a multi-tone optical comb, the method comprising the steps of:

modulating an optical signal from a laser with an optical modulator to provide a modulated optical signal;

delaying said modulated optical signal in a first optical branch to provide a first delayed optical signal;

propagating said modulated optical signal in a forward direction in a second optical branch to provide a second delayed optical signal;

generating Stokes light from said modulated optical signal;

injecting said Stokes light into said second optical branch so that said Stokes light propagates in a reverse direction to said modulated optical signal in said second optical branch, wherein said Stokes light acts as a seed for stimulated Brillouin scattering in said second optical branch;

photodetecting said first delayed optical signal and said second delayed optical signal to produce an electrical signal; and

controlling said optical modulator with said electrical signal.

7. The apparatus of claim 1 or 2, wherein the photonic oscillator comprises multiple loops including:

(i) a first optical delay line in a first loop for spacing a comb generated by the a multi-tone optical comb generator;

(ii) a second optical delay line in a second loop line for noise reduction, the second delay line being longer than the first optical delay line;

(iii) at least one photodetector connected to the first and second delay lines; and

(iv) an optical intensity modulator in a loop portion common to the first and second loops for driving the first and second optical delay lines.

8. The apparatus of claim 7, wherein the loop common portion further includes an amplifier and a band pass filter.

9. The apparatus of claim 8, wherein the amplifier is an electronic amplifier.

10. The apparatus of claim 7, wherein the loop common portion further includes a band pass filter and wherein at least one of the first and second loops includes an optical amplifier therein.

11. The apparatus of claim 7, further including means for compensating for environmental changes affecting a length of at least one of the first and second optical delay lines.

12. The apparatus of claim 11, wherein the means for compensating for environmental changes affecting the length of at least one of the first and second optical delay lines comprises an apparatus for adjusting the length of at least one of the first and second optical delay lines and a feedback circuit including a tone selection filter to the loop common portion and a mixer for mixing the output of the tone selection filter with a reference signal, an output of the mixer being operatively coupled to the length adjusting apparatus.

13. The apparatus of claim 12, wherein the tone selection filter is coupled to the optical intensity modulator.

14. The apparatus of claim 13, wherein the optical intensity modulator is an electro-absorption modulator having an electrical output coupled to the tone selection filter.

15. The apparatus of claim 12, wherein the length adjusting apparatus adjusts the length of both of the first and second optical delay lines.

16. The apparatus of claim 11, wherein the means for compensating for environmental changes affecting the length of at least one of the first and second optical delay lines comprises a phase shifter disposed in the loop common portion and a feedback circuit including a tone selection filter coupled to the loop common portion and a mixer for mixing the output of the tone selection filter with a reference signal, an output of the mixer being operatively coupled to the phase shifter.

17. The apparatus of claim 16, wherein the tone selection filter is coupled to the optical intensity modulator.

18. The apparatus of claim 17, wherein the optical intensity modulator is an electro-absorption modulator having an electrical output coupled to the tone selection filter.

19. The apparatus of claim 7, further including a injection seeding circuit for seeding the photonic oscillator.

20. The apparatus of claim 7, wherein the second optical delay line is more than 40 times longer than the first optical delay line.

21. The apparatus of claim 7, further including an optical intensity modulator, the optical intensity modulator being responsive to an RF input signal and to the series of RF comb lines on the optical carrier generated by the photonic oscillator for generating an optical signal which is applied to said photodetector.

22. The apparatus of claim 7, further including an optical coupler responsive to an RF input signal, the optical coupler being connected to receive the series of RF comb lines on the optical carrier generated by the photonic oscillator and the frequency translation reference generated by the second laser, the optical coupler being connected either upstream or downstream of the optical intensity modulator which is responsive to the RF input signal.

23. The apparatus of claim 22, wherein the RF input signal includes a pulsed code or polyphased codes.

24. The apparatus of claim 1 or 2, wherein the photonic oscillator comprises:
a first optical branch comprising a first optical delay element;
a second optical branch comprising a main optical fiber having a forward direction of light propagation,
a common path, said common path comprising:
an optical portion having an optical modulator providing an optical signal to said first optical branch and said second optical branch, and
an electrical portion having at least one photodetector coupled to said first optical branch and said second optical branch, said at least one photodetector producing an electrical signal coupled to said optical modulator; and
a third optical branch, said third optical branch providing a Stokes beam to said second optical branch, said Stokes beam propagating in said main optical fiber in a direction opposite to said forward direction of light propagation.

25. The apparatus of any one of claims 3, 4, or 24, wherein said electrical portion comprises:
a first photodetector coupled to said first optical branch;
a second photodetector coupled to said second optical branch;
an electrical combiner coupled to said first photodetector and said second photodetector and producing a combined electrical output; and
a bandpass filter receiving said combined electrical output and providing a filtered electrical signal to said optical modulator.

26. The apparatus of any one of claims 3, 4, or 24, wherein said common path further comprises at least one element of the group of elements consisting of an electrical amplifier, an optical amplifier, an electrical phase shifter, and an optical phase shifter.

27. The apparatus of any one of claims 3, 4, or 24, wherein said common path further comprises a variable optical coupler, said variable optical coupler having an input receiving said optical signal, and having a first adjustable output coupled to said first optical branch, a second adjustable output coupled to said second optical branch, and a third adjustable output.

28. The apparatus of any one of claims 3, 4, or 24, wherein at least one optical branch of said first and second optical branches further comprises at least one element of the group of elements consisting of an optical amplifier and a variable optical attenuator.

29. The apparatus of any one of claims 3, 4, or 24, wherein said first optical delay element comprises optical fiber.

30. The apparatus of any one of claims 3, 4, or 24, wherein said Stokes beam is produced by stimulated Brillouin scattering in said main optical fiber and said main optical fiber has an input and an output and said third optical branch comprises:
an optical amplification path, said optical amplification path having an input and an output;
a first optical circulator, said first optical circulator coupling said optical signal to said input of said main optical fiber and coupling said Stokes beam to said input of said optical amplification path; and
a second optical circulator, said second optical circulator coupling said output of said optical amplification path to said main optical fiber and coupling said output of said main optical fiber to said at least one photodetector.

31. The apparatus of claim 30, wherein said optical amplification path comprises one or more optical amplifiers or one or more optical amplifiers and one or more variable optical attenuators.

32. The apparatus of any one of claims 3, 4, or 24, wherein said main optical fiber has an input and an output and wherein said second optical branch further comprises an optical splitter having a first splitter output and a second splitter output, the second splitter output directing said optical signal to said input of said main optical fiber, and

wherein said third optical branch comprises:

an optical amplification path having an input and an output;

a loop of optical fiber, said Stokes beam produced by stimulated Brillouin scattering in said loop of optical fiber;

a 2 x 2 optical coupler having at least three ports, a first port of said 2 x 2 optical coupler coupled to a first end of loop of optical fiber, a second port of said 2 x 2 optical coupler coupled to a second end of said loop of optical fiber, and a third port of said 2 x 2 optical coupler coupling said Stokes beam into and out of said loop of optical fiber;

a first optical circulator having at least three ports, wherein a first port of said first optical circulator is coupled to said first splitter output and a second port of said first optical circulator coupled to said input of said optical amplification path, and a third port of said first optical circulator is coupled to said third port of said 2 x 2 optical coupler, said first optical circulator directing said optical signal to said loop of optical fiber and directing said Stokes beam to said optical amplification path; and,

a second optical circulator, said second optical circulator coupling said output of said optical amplification path to said main optical fiber and coupling said output of said main optical fiber to said at least one photodetector.

33. The apparatus of claim 32, wherein said optical amplification path comprises one or more optical amplifiers or one or more optical amplifiers and one or more variable optical attenuators.

34. The apparatus of claim 32, wherein a fraction of said optical signal is directed to said loop of optical fiber and said loop of optical fiber has a length sufficient to ensure a Stokes seed is generated.

35. The apparatus of claim 32, wherein said loop of optical fiber has one or more optical amplifiers.

36. The apparatus of claim 32, wherein the coupling strength of said 2 X 2 optical coupler is adjustable.

37. The apparatus of claim 32, wherein said second optical branch further comprises an optical isolator blocking said Stokes beam from coupling into said common path.

38. The apparatus of claim 32, wherein said second optical branch further comprises a third optical circulator disposed between said second splitter output and said input to said main optical fiber.

39. The method of claim 5, further including the step of heterodyning the lightwave waveform.

40. The method of claim 39, wherein the step of heterodyning is performed by at least one photodetector.

41. The method of claim 5, wherein the multi-tone optical comb is generated by a photonic oscillator and further including the following steps:
(i) optically delaying the comb in a first loop for spacing comb lines in the comb;
(ii) optically delaying the comb in a second loop line for noise reduction, a second optical delay caused by step (ii) being longer than a first optical delay caused by step (i);
(iii) photodetecting the delayed comb; and
(iv) using the delayed comb in an optical intensity modulator to modulate an output of a laser to thereby generate said multi-tone optical comb as a series of RF comb lines on an optical carrier.

42. The method of claim 41, wherein a loop common portion further includes an amplifier for amplifying the comb and a band pass filter for establishing a bandwidth of the comb.

43. The method of claim 42, wherein the amplifying is performed electronically.

44. The method of claim 41, wherein a loop common portion includes a band pass filter for establishing a band width of the comb and further including a step of optically amplifying the comb in at least one of the first and second loops.

45. The method of claim 41, further including the step of compensating for environmental changes by changing the amount of at least one of the first and second optical delays.

46. The method of claim 45, wherein the step of compensating for environmental changes by changing an amount of at least one of the optical delays is performed by comparing frequency or phase of one comb line in the comb with a reference and adjusting a length of at least one optical delay line carrying the comb.

47. The method of claim 46, wherein the adjusting step adjusts the length of first and second optical delay lines.

48. The method of claim 45, wherein the step of compensating for environmental changes by changing an amount of at least one of the optical delays is performed by comparing frequency or phase of one comb line in the comb with a reference and adjusting a phase of the comb.

49. The method of claim 41, further including the step of seeding the photonic oscillator to initiate the comb.

50. The method of claim 41, wherein the second optical delay is more than 40 times longer than is the first optical delay.

51. The method of claim 5, further including the step of intensity modulating the comb with an optical intensity modulator responsive to an RF input signal and to the series of RF comb lines on the optical carrier for modulating said lightwave waveform.

52. The method of claim 51, wherein the RF input signal applies a pulsed code or polyphased codes to the optical intensity modulator.

53. The method of claim 5, further including the step of modulating the intensity of the comb and the frequency translation reference with an optical intensity modulator responsive to an RF input signal and to the series of RF comb lines on the optical carrier and to the frequency translation reference for modulating said lightwave waveform.

54. The method of claim 53, wherein the RF input signal applies a pulsed code or polyphased codes to the optical intensity modulator.

55. The method of claim 5, wherein the step of generating a multi-tone optical comb comprises:

modulating an optical signal from a laser with an optical modulator to provide a modulated optical signal;

delaying said modulated optical signal in a first optical branch to provide a first delayed optical signal;

propagating said modulated optical signal in a forward direction in a second optical branch to provide a second delayed optical signal;

generating Stokes light from said modulated optical signal;

injecting said Stokes light into said second optical branch so that said Stokes light propagates in a reverse direction to said modulated optical signal in said second optical branch, wherein said Stokes light acts as a seed for stimulated Brillouin scattering in said second optical branch;

photodetecting said first delayed optical signal and said second delayed optical signal to produce an electrical signal; and

controlling said optical modulator with said electrical signal.

56. The method of claim 6 or 55, wherein said first optical branch comprises optical fiber and said second optical branch comprises optical fiber.

57. The method of claim 6 or 55, wherein said method further comprises at least one step of the group of steps consisting of a step of amplifying said electrical signal, a step of band pass filtering the electrical signal, and a step of phase shifting the electrical signal.

58. The method of claim 6 or 55, further comprising the steps of
directing said modulated optical signal to said first optical branch from a first output of a variable optical coupler;
directing said modulated optical signal to said second optical branch from a second output of said variable optical coupler;
providing said multi-tone optical comb from a third output of said variable optical coupler; and
controlling a output power level of at least one output of said first output, said second output, and said third output.

59. The method of claim 6 or 55, wherein at least one optical branch of the first and second optical branches comprises at least one element of the group of elements consisting of an optical amplifier and a variable optical attenuator.

60. The method of claim 6 or 55, wherein said second optical branch comprises a main optical fiber and said step of generating Stokes light comprises the steps of:
directing said modulated optical signal into said main optical fiber, wherein said Stokes light is produced by stimulated Brillouin scattering in said main optical fiber;
directing said reverse propagating Stokes light from said second optical branch to an optical amplification path with an optical circulator; and
amplifying said Stokes light.

61. The method of claim 60, further comprising the step of variably attenuating said Stokes light.

62. The method of claim 6 or 55, wherein said step of generating Stokes light comprises the steps of:
directing said modulated optical signal to a recirculating ring, wherein said Stokes light is produced by stimulated Brillouin scattering in said recirculating ring; and
coupling said Stokes light out of said recirculating ring.

63. The method of claim 62 further comprising the step of amplifying said Stokes light prior to injecting said Stokes light into said second optical branch.

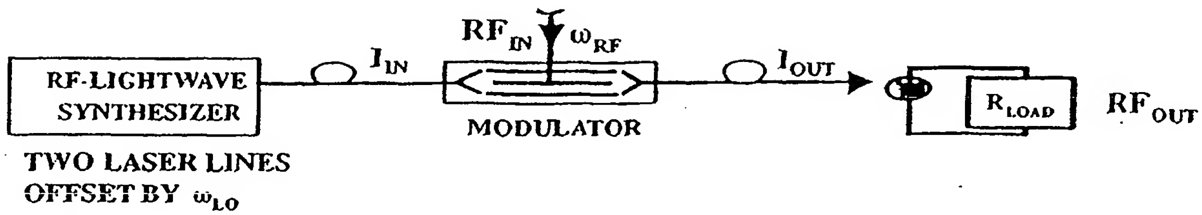


Figure 1 prior art

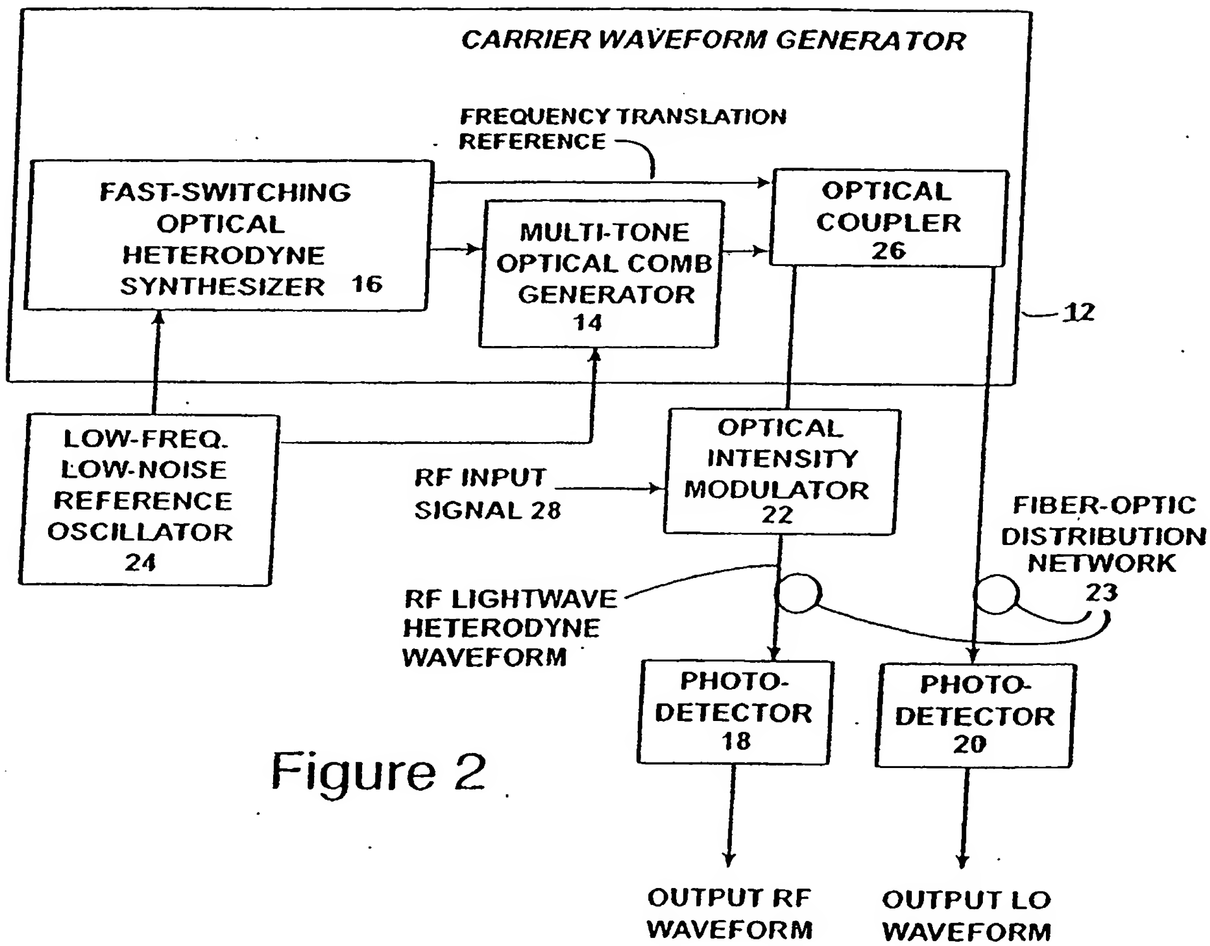

CARRIER WAVEFORM GENERATOR
FREQUENCY TRANSLATION REFERENCE
FAST-SWITCHING OPTICAL HETERODYNE SYNTHESIZER 16
MULTI-TONE OPTICAL COMB GENERATOR 14
OPTICAL COUPLER 26
12
LOW-FREQ. LOW-NOISE REFERENCE OSCILLATOR 24
RF INPUT SIGNAL 28
OPTICAL INTENSITY MODULATOR 22
FIBER-OPTIC DISTRIBUTION NETWORK 23
RF LIGHTWAVE HETERODYNE WAVEFORM
PHOTO-DETECTOR 18
PHOTO-DETECTOR 20
OUTPUT RF WAVEFORM
OUTPUT LO WAVEFORM

Figure 2

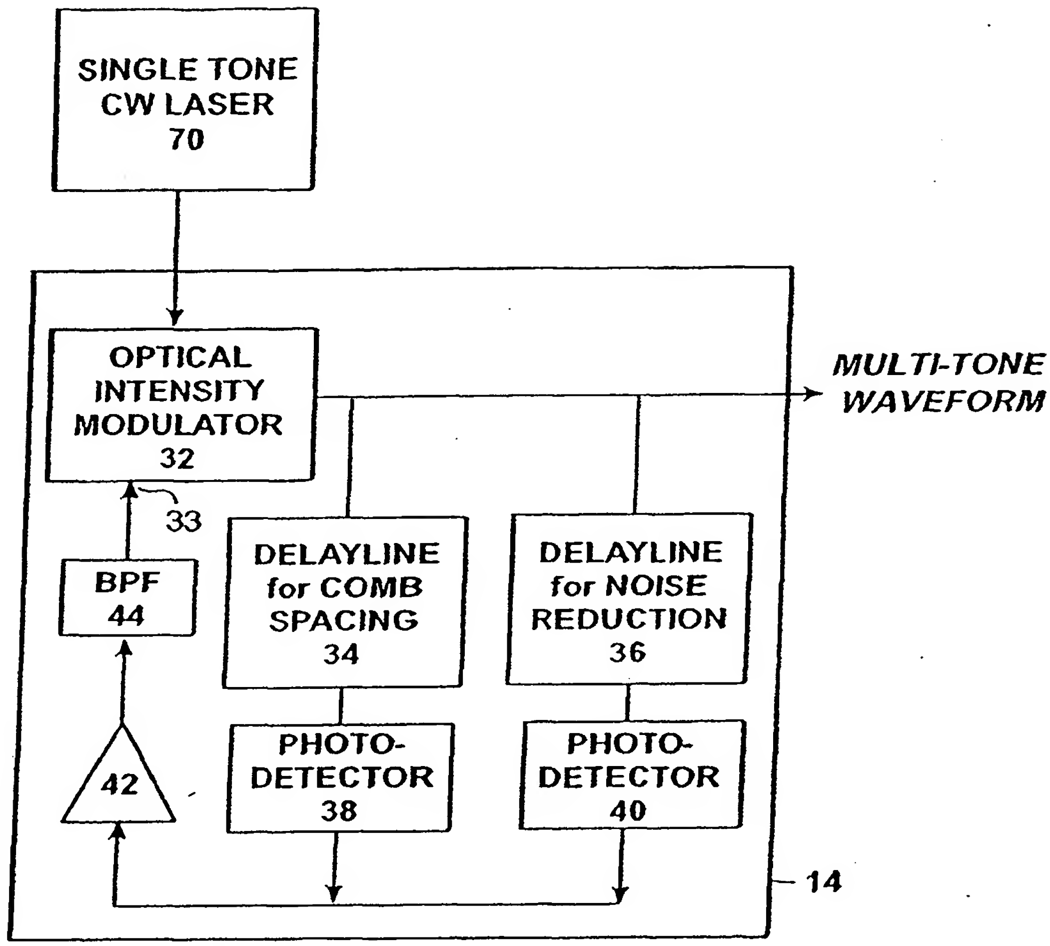

SINGLE TONE
CW LASER
70
OPTICAL
INTENSITY
MODULATOR
32
MULTI-TONE
WAVEFORM
33
BPF
44
DELAYLINE
for COMB
SPACING
34
DELAYLINE
for NOISE
REDUCTION
36
42
PHOTO-
DETECTOR
38
PHOTO-
DETECTOR
40
14

Figure 3

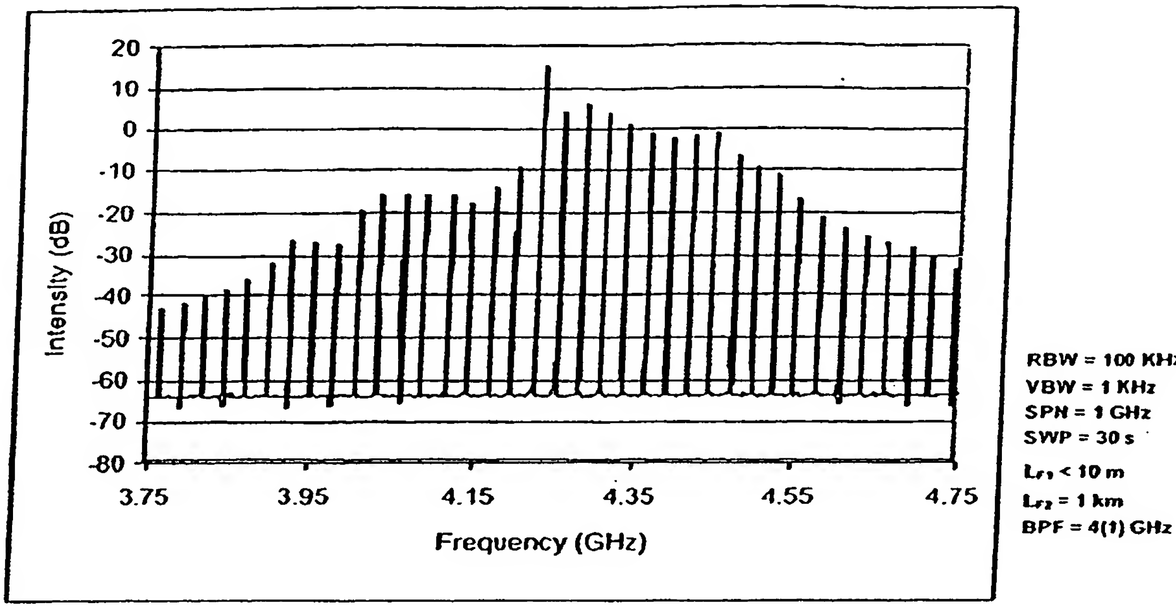


Figure 4

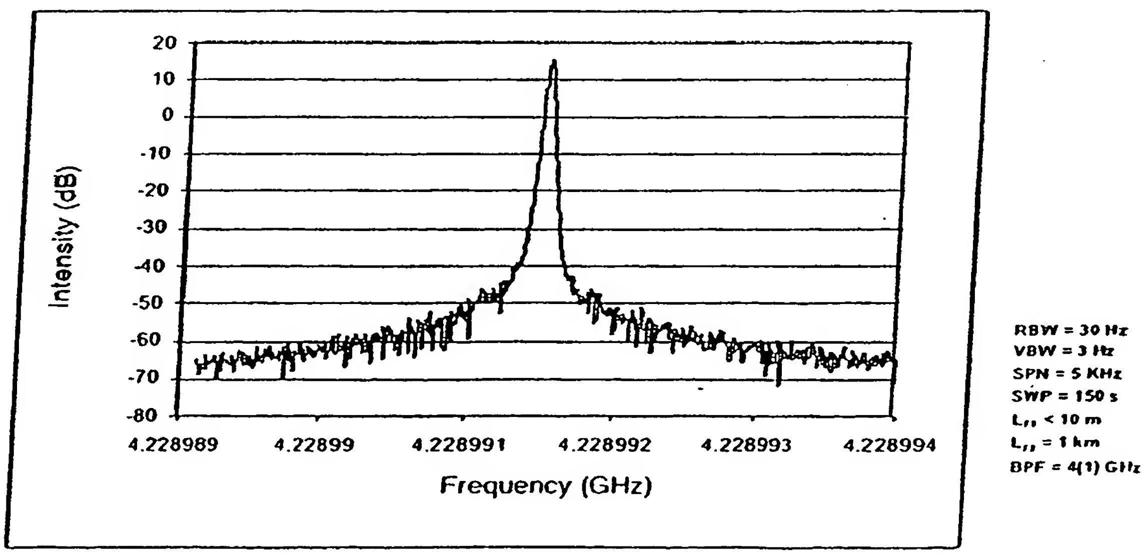
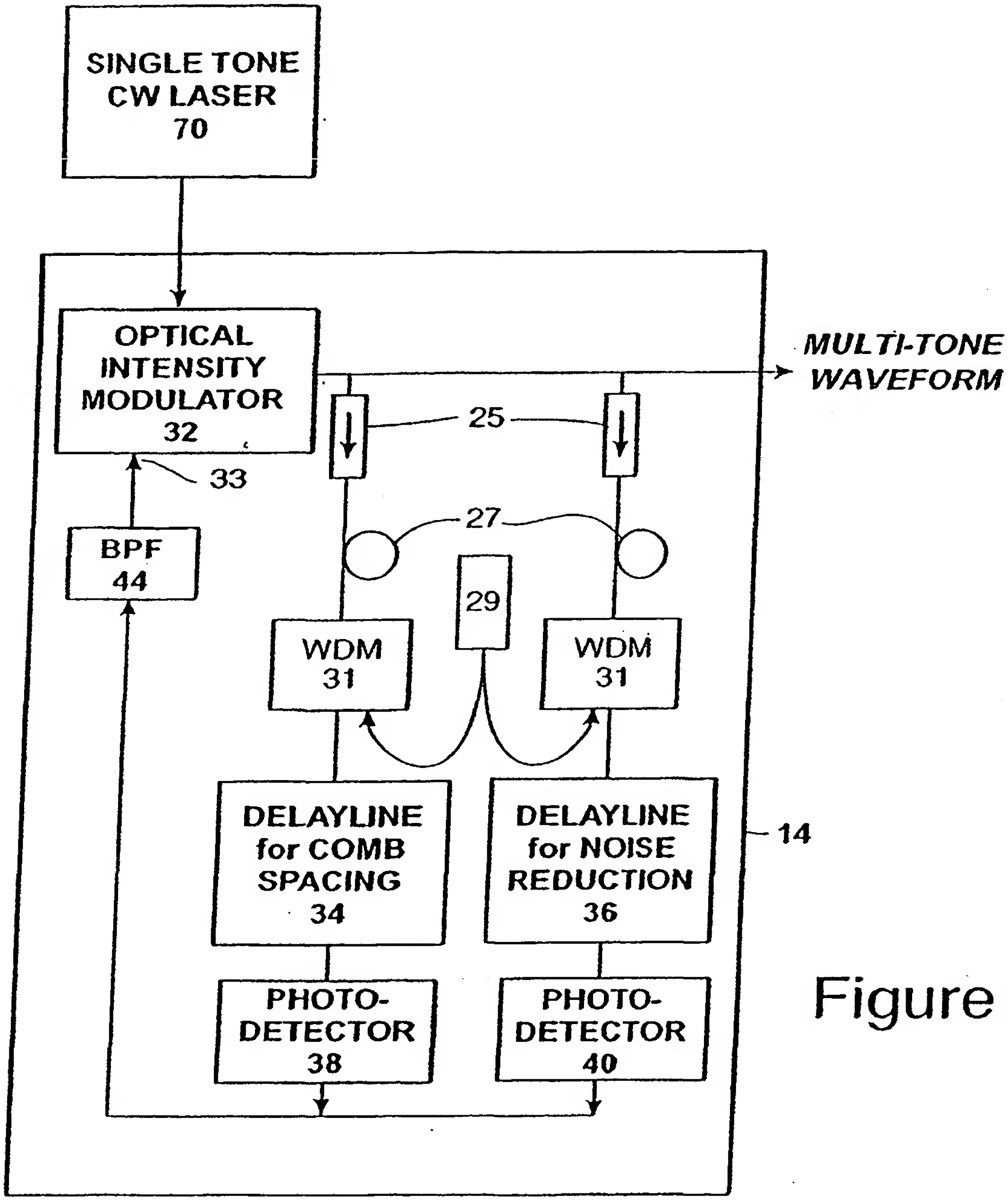


Figure 5



SINGLE TONE CW LASER 70
OPTICAL INTENSITY MODULATOR 32
MULTI-TONE WAVEFORM
25
33
27
BPF 44
29
WDM 31
WDM 31
DELAYLINE for COMB SPACING 34
DELAYLINE for NOISE REDUCTION 36
14
PHOTO-DETECTOR 38
PHOTO-DETECTOR 40

Figure 6

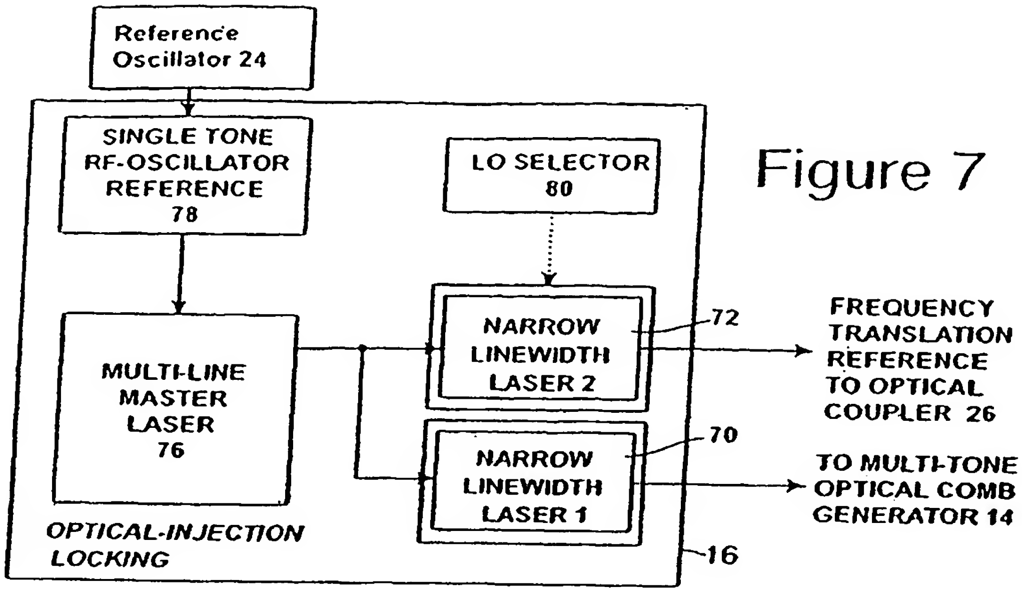


Figure 7

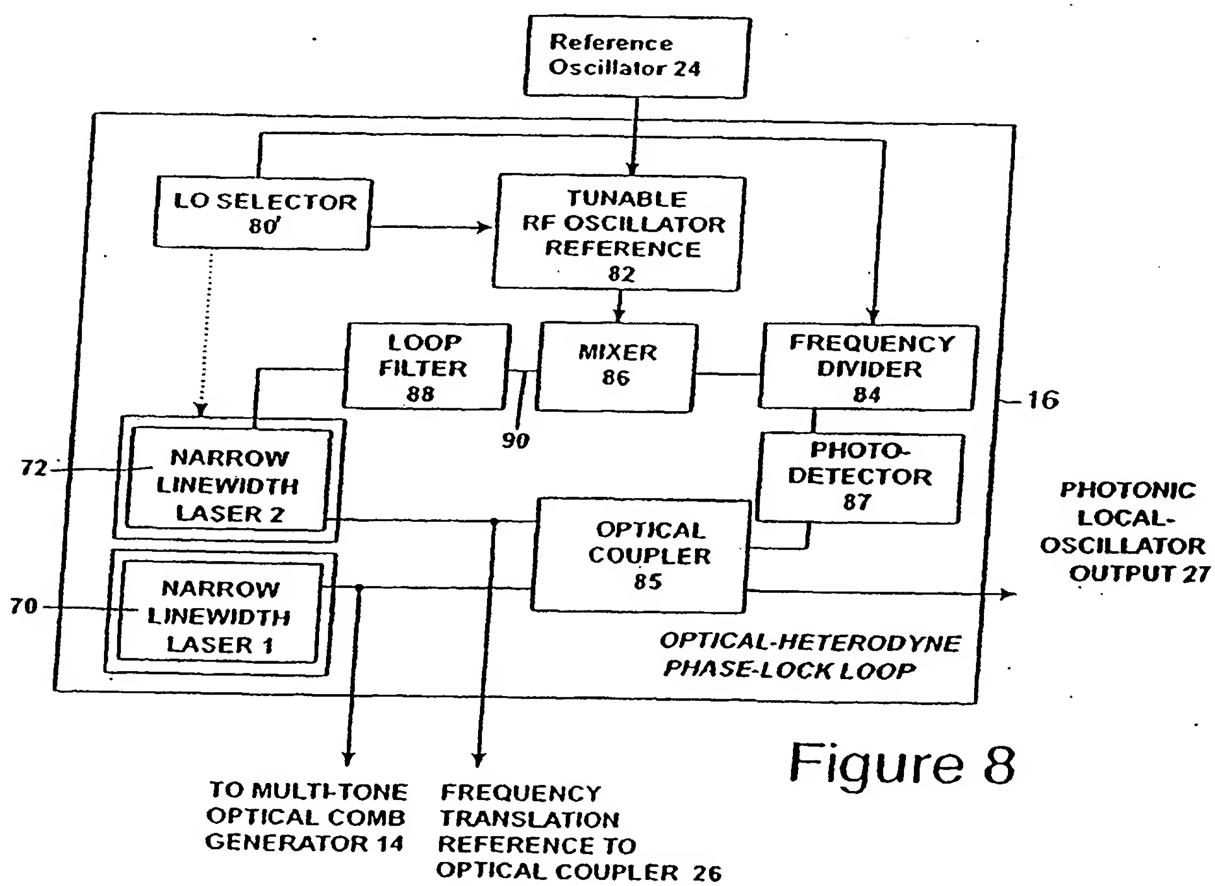


Figure 8

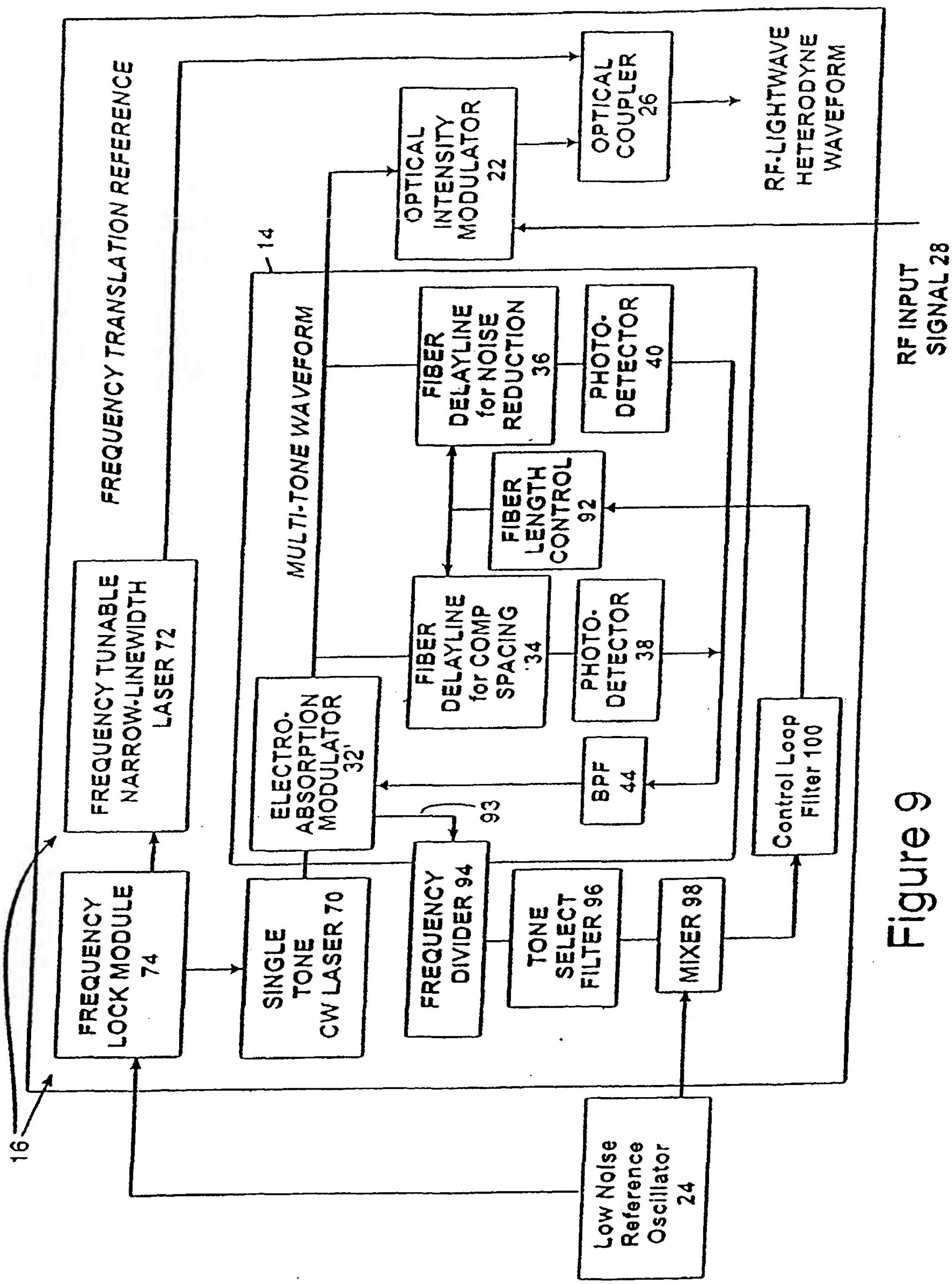

FREQUENCY TRANSLATION REFERENCE
OPTICAL INTENSITY MODULATOR 22
OPTICAL COUPLER 26
RF-LIGHTWAVE HETERODYNE WAVEFORM
RF INPUT SIGNAL 28
14
MULTI-TONE WAVEFORM
FIBER DELAYLINE for NOISE REDUCTION 36
PHOTO-DETECTOR 40
FIBER LENGTH CONTROL 92
FIBER DELAYLINE for COMP SPACING 34
PHOTO-DETECTOR 38
FREQUENCY TUNABLE NARROW-LINEWIDTH LASER 72
ELECTRO-ABSORPTION MODULATOR 32'
BPF 44
93
Control Loop Filter 100
FREQUENCY LOCK MODULE 74
SINGLE TONE CW LASER 70
FREQUENCY DIVIDER 94
TONE SELECT FILTER 96
MIXER 98
16
Low Noise Reference Oscillator 24

Figure 9

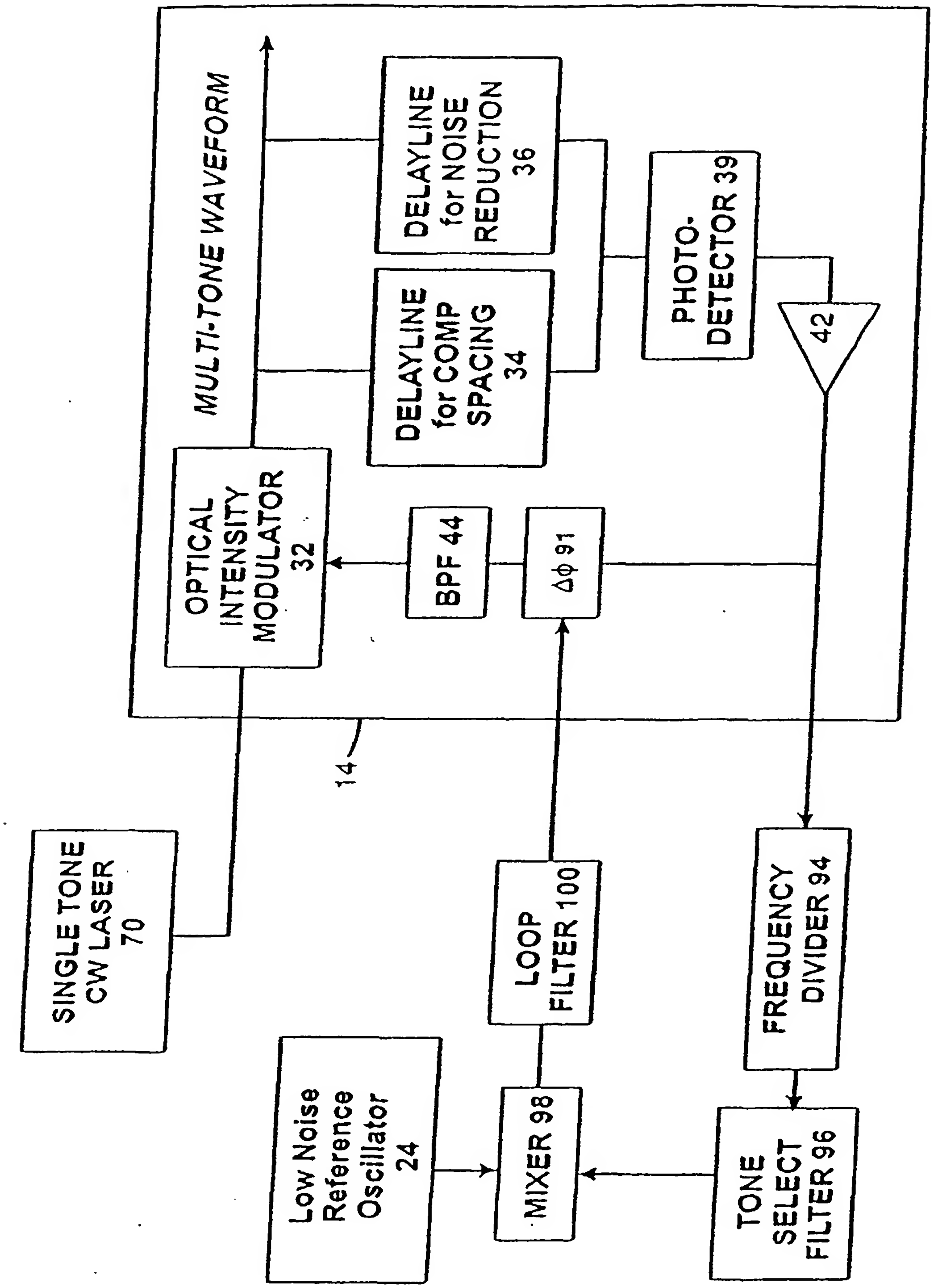

MULTI-TONE WAVEFORM
DELAYLINE for NOISE REDUCTION 36
DELAYLINE for COMP SPACING 34
PHOTO-DETECTOR 39
42
OPTICAL INTENSITY MODULATOR 32
BPF 44
Δφ 91
14
SINGLE TONE CW LASER 70
LOOP FILTER 100
FREQUENCY DIVIDER 94
Low Noise Reference Oscillator 24
MIXER 98
TONE SELECT FILTER 96

Figure 10

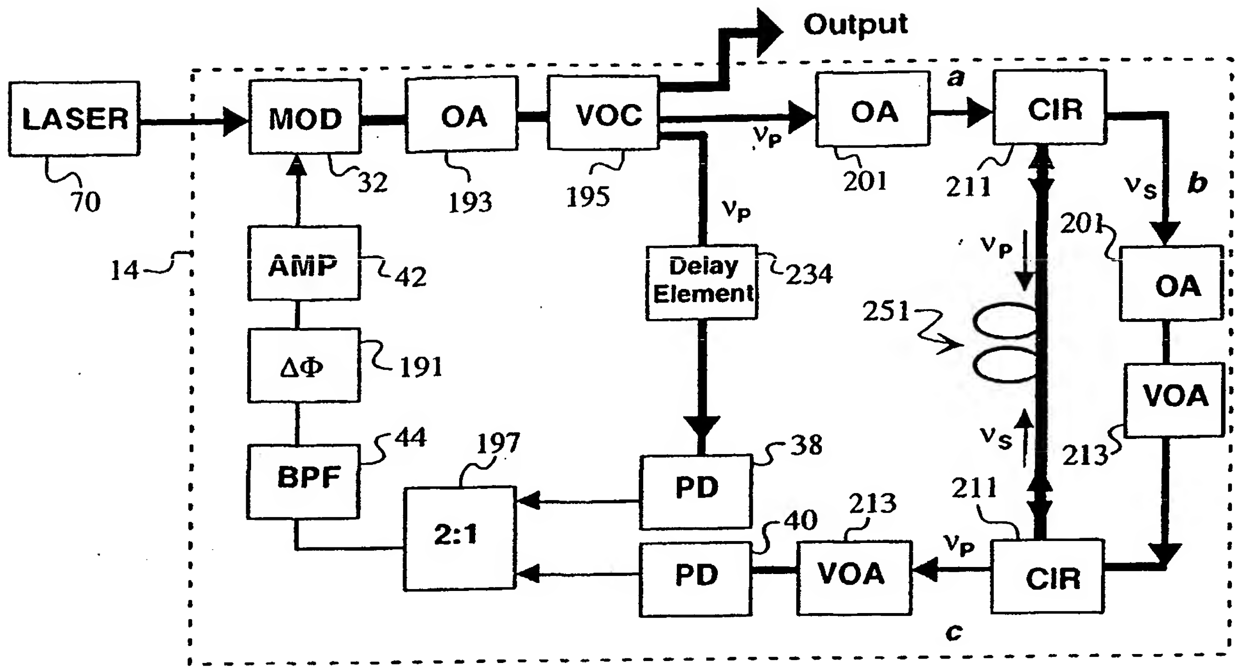

Output
LASER
MOD
OA
VOC
OA
CIR
a
70
32
193
195
ν_P
201
211
ν_S
b
ν_P
201
14
AMP
42
Delay Element
234
ν_P
251
OA
ΔΦ
191
VOA
ν_S
213
44
197
38
BPF
PD
211
2:1
40
213
ν_P
PD
VOA
CIR
c

FIG. 11

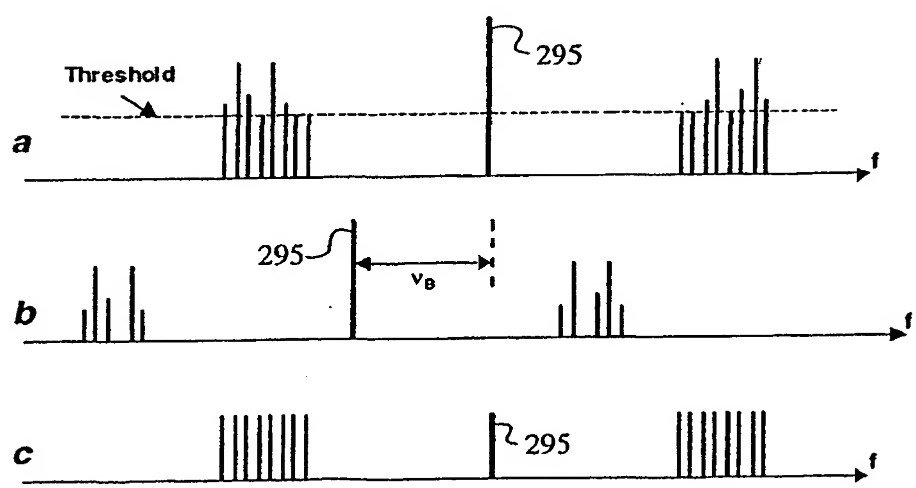
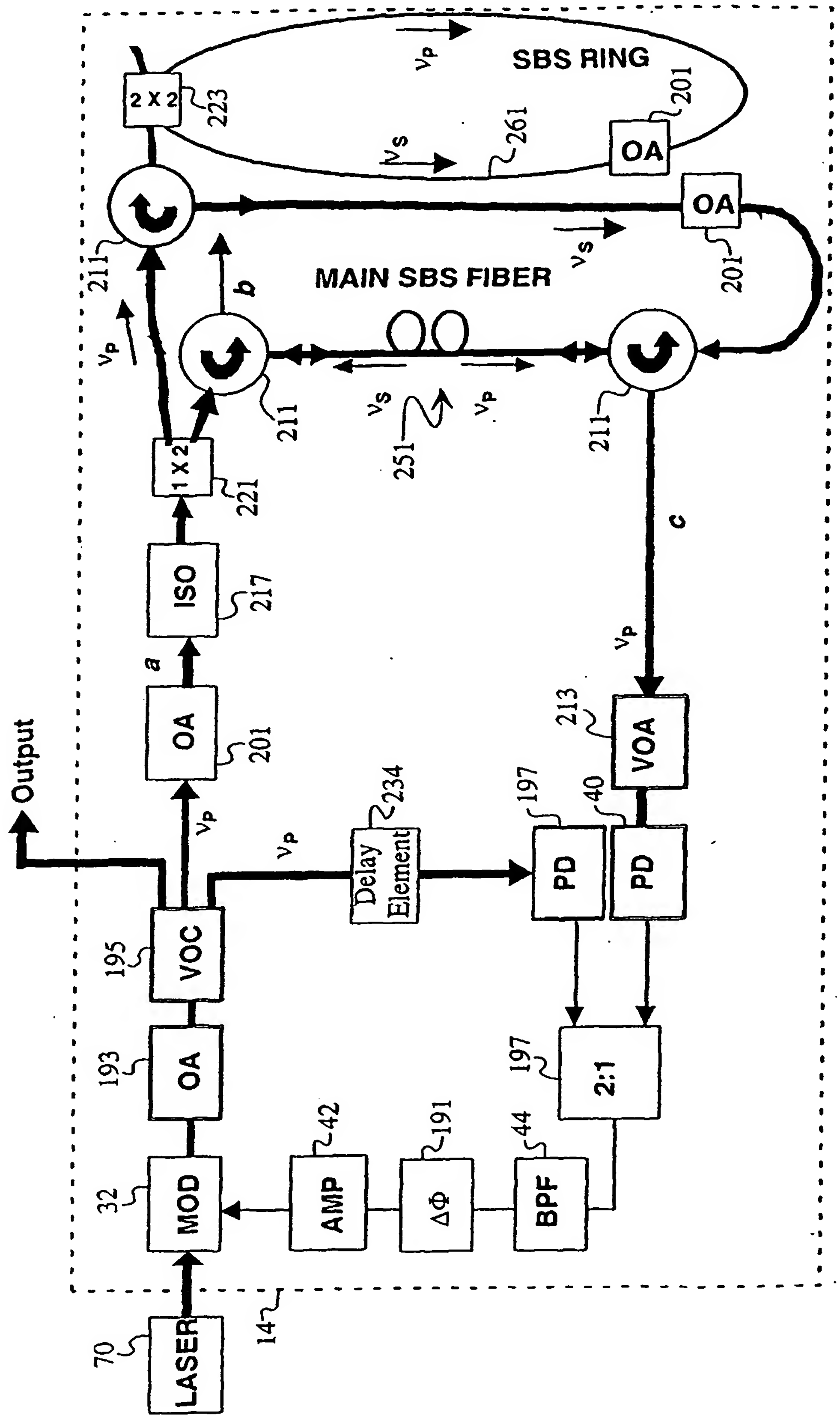

295
Threshold
a
f
295
ν_B
b
f
c
295
f

FIG. 12



SBS RING
MAIN SBS FIBER
2 X 2
1 X 2
OA
ISO
VOC
MOD
LASER
AMP
ΔΦ
BPF
2:1
PD
PD
VOA
Delay Element
Output
a
b
c
v_P
v_S
223
261
201
211
221
217
251
213
197
40
234
195
193
32
70
42
191
44
14

FIG. 13